STABILITY CALCULATION FOR THE SURROUNDING ROCK OF POWERHOUSE CAVERN

[UPPER TRISHULI-1 HEP (216MW)]

2022. 05

DOOSAN Enerbility

FOR APPROVAL

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1 General

1.1 Introduction

The underground powerhouse is located within the right bank mountain of Trishuli river with vertical buried depth of about 300m. At present, overall size of powerhouse cavern is L80.0m×W20.6m×H39.4m, size of main transformer cavern, which is located at downside of powerhouse cavern and with net rock wall thickness of about 27.75m, is W15.6m×H12.3m.

According to the previous geological information and contractor's interpretation, inter bedded mica schist and quartz-schist are developed / distributed along cavern axis and are assumingly classified as Type II or Type III. The proposed supports of powerhouse and transformer caverns are shown in Figure ~1-2. The staged excavation is shown in Figure 1-3.

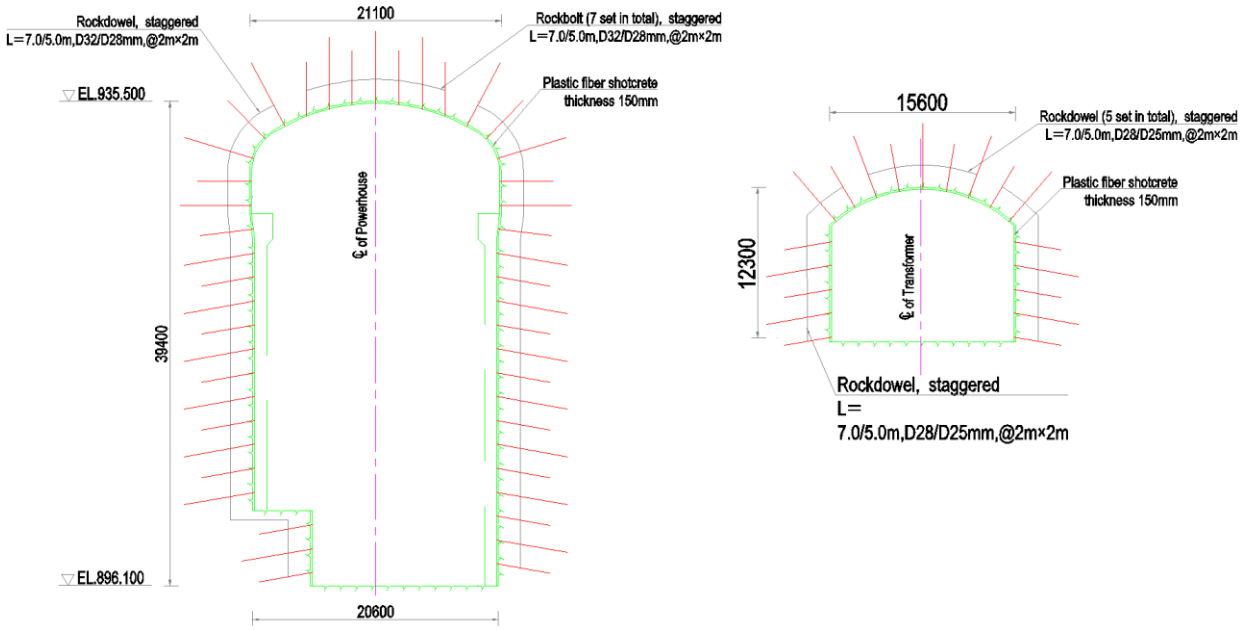


Figure 1-1 Proposed supports of powerhouse and transformer caverns (rock type II)

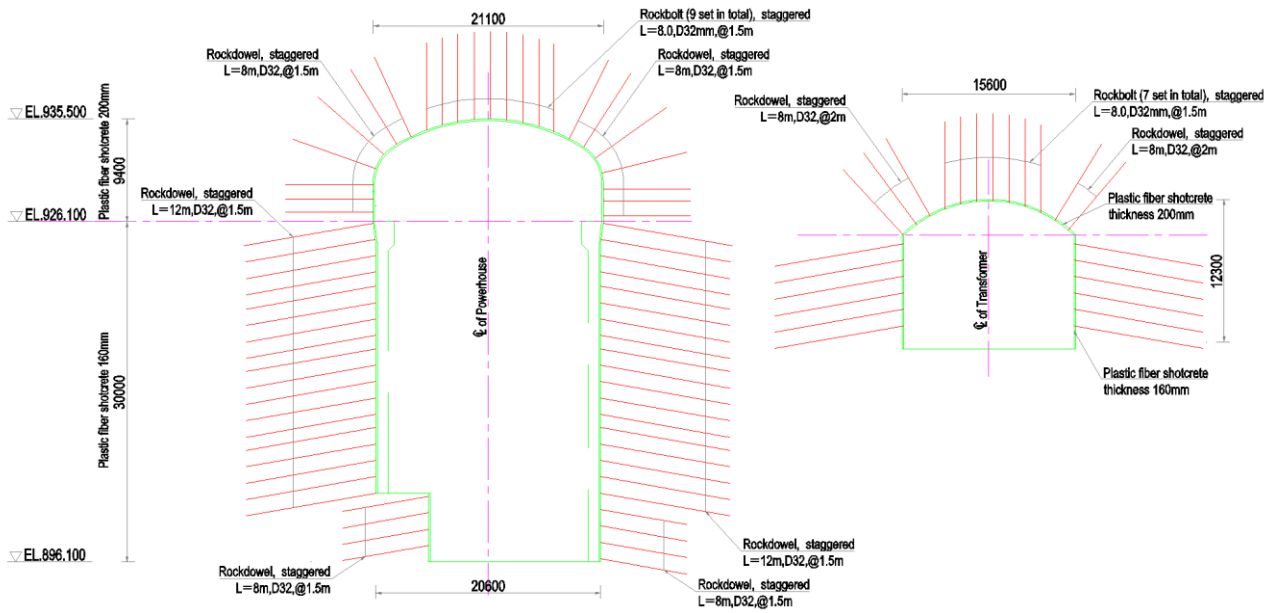


Figure 1-2 Proposed supports of powerhouse and transformer caverns (rock type III)

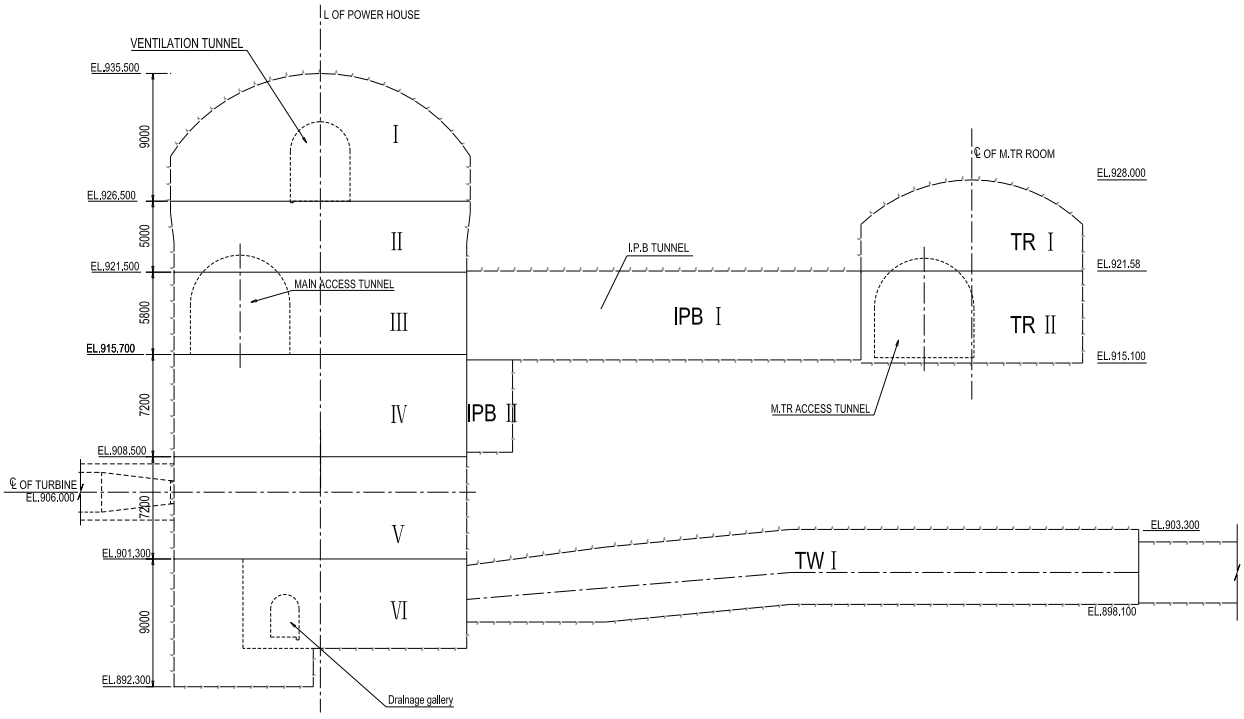


Figure 1-3 Staged excavation plan of powerhouse and transform cavern

1.2 Design Objective

This calculation is aim to verify the proposed supports include rock dowels and shotcrete be effective and feasible; ensure stability of caverns and safety of construction activities during cavern excavation. Further 3-

D stability analysis is planned to be conducted to provide more reliable information to support design of powerhouse and main transformer caverns.

1.3 References

(1) Contract documents, Employer's Requirement

(2) Tunnels and Shafts in Rock (EM 1110-2-2901)

(3) Regarding general Powerhouse size determination confirmation UT1-HEP-PC-DHI-2022-0271

(4) High Strength Deformed Steel Bars and Wires for Concrete Reinforcement Specification (Fourth Revision) (IS 1786-2008)

(5) Building Code Requirements for Structural Concrete and Commentary (ACI 318)

2 Theoretical Background of Calculations

2.1 Software

Software Phase 2 is applied to conduct the calculation. Phase2 is a powerful 2D finite element program for soil and rock applications. Phase2 can be used for a wide range of engineering projects including excavation design, slope stability, groundwater seepage, probabilistic analysis, consolidation, and dynamic analysis capabilities.

Software UNWEDGE is an interactive software for the stability analysis of three-dimensional wedge formed by structural discontinuity and underground excavation, which is used to analyze the underground excavation problem with discontinuous structural plane in rock mass. UNWEDGE calculates the safety factor of potentially unstable wedge, and can analyze the influence of support system on wedge stability.

2.2 Modeling Conditions, Material Law, Constitutive Model

The modeling conditions are plane strain. The material law is elasto-plastic combined with strain-softening (for rock). The rock mass is modeled as a continuum, homogeneous and isotropic. The failure criteria are the Mohr-Coulomb failure criteria. What needs to be emphasized is that such continuum model with homogeneous and isotropic material is a model, only, and does not necessarily reflect reality. In reality, the displacements occur in blocky rock masses always along discontinuities (joints, foliation etc.), which leads to loosening of the rock mass. The determined plastic zone in the continuums model represents an area of the rock mass where

rock blocks were displaced to each other (= loosening of rock mass). In reality, it does not represent an area where the material was subject to plastic flow, as in soil.

2.3 In situ horizontal stress

For unavailability of field measurement of in situ stresses at the area, gravitational stresses are adopted.

The vertical stress due to the overlying rock is:

$$\sigma_z = \gamma h$$

Where γ represents the density that is the unit weight of the rock.

The horizontal in situ stresses also depend on the depth below surface. They are generally defined in terms of the vertical stress as follows:

$$K_0 = \sigma_h / \sigma_v$$

Where K_0 represents the lateral rock stress ratio. Since there are three principal stresses directions, there will be two horizontal principal stresses. In an undisturbed rock mass, the two horizontal principal stresses may be equal.

In this calculation, K_0 is taken as 1.3 according to topographic and geological conditions of the engineering area.

3 Properties of Materials

3.1 Rock Mass

The mechanical parameters of surrounding rock are shown in Table 3-1 as per approval letter RN 0031.

Table 3-1 Mechanical parameter for surrounding rock of powerhouse caverns

Class of surrounding rock	Q	Unit weight	Poisson 's ratio of rock mass	Elastic modulus of rock mass	Rock mass/rock mass shear (shearing) strength				Uniaxial compressive strength of rock mass	Uniaxial compressive strength of intact rock	Tensile strength of rock mass
					Peak		Residual				
		γ (kN/m^3)	μ	Em （GPa）	*C （MPa）*	*Φ （°）*	*Φr （°）*	*Cr （MPa）*	UCS rm （MPa）	INTACT UCS r （MPa）	σ_{tm} (MPa)
II	10~40	27.0	0.25	20.5	2.5	48	38	0.95	13.0	60	1.3
III	7~10	26.5	0.25	10.0	1.0	45	35	0.35	4.8	60	0.48

3.2 Rock Dowel/Rock Bolt

1) Dowel type: cement mortar full length bonded dowel

2) Yield strength: 500MPa

3) Tensile strength: 545MPa (Table 3 of "IS 1786-2008")

4) Elastic modulus: 210000MPa

5) Allowable tensile strength of rock bolt steel: 500MPa/1.5=333MPa. The value 1.5 is safety factor.

3.3 Shotcrete

The mechanical parameters of plastic fiber shotcrete are shown in Table 3-2. Elastic modulus is calculated by formula Ec=4700*fc'^0.5 (ACI 318, section 19.2.2 Modulus of elasticity).

Table 3-2 Mechanical parameter of plastic fiber shotcrete

Compressive strength fc'(MPa)	Tensile Strength (MPa)	Elastic modulus Ec (MPa)	Unit Weight (kN/m^3)	Poisson ratio
25	2.5	23500	24.0	0.2

4 Cavern Support

4.1 Cavern Support per Excavation Class

The proposed supports for each rock type are shown in Table 4-1.

Table 4-1 Proposed supports for each rock type

Item	Unit	proposed supports	
		II	III
Shotcrete thickness	mm	150mm	Roof :200mm Side wall: 160mm
Shotcrete strength	MPa	25	25
Powerhouse cavern supports		Roof and side walls: L=7.0m,φ32mm/L=5.0m,φ 28mm staggered. Amongst, rock bolts are proposed in the central portion of the cavern crown.	Roof: L=8.0m,φ32mm Side walls: L=12.0m,φ32mm Lower side walls: L=8.0m,φ32mm. Amongst, rock bolts are proposed in the central portion of the cavern crown.
Transformer cavern supports		Roof and side walls: L=7.0m,φ28mm/ L=5.0m,φ 25mm. Amongst, rock bolts are proposed in the central portion of the cavern crown.	Roof: L=8.0m,φ32mm Side walls: L=12.0m,φ32mm. Amongst, rock bolts are proposed in the central portion of the cavern crown.
Rock dowels and/or rock bolts spacing within each row	m	2.0	1.5
Rock dowels and/or rock bolts row spacing	m	2.0	1.5

4.2 Safety Factor

The support safety factor for shotcrete is 1.2.

The minimum safety factor for wedges analysis is 2.0.

5 Model Set-up, Boundary and Loading Conditions, Stress Initiation

For the case of gravitational loading, only, boundary and loading conditions to be set as shown below. The

lower boundary of the counted domain is fixed in the X and Y directions, two lateral boundaries fixed in the X direction but unconstrained in the Y direction, and the top is free. The load of overburden above the top boundary is automatically applied by the software according to the elevations. Initial stress conditions in the model can be calculated by gravitational loading, or by specifying the relative ground surface elevation.

The finite element model for rock class II and III is shown as Figure 5-1, and the corresponding gravitational loading is shown in the

Table 5-1.

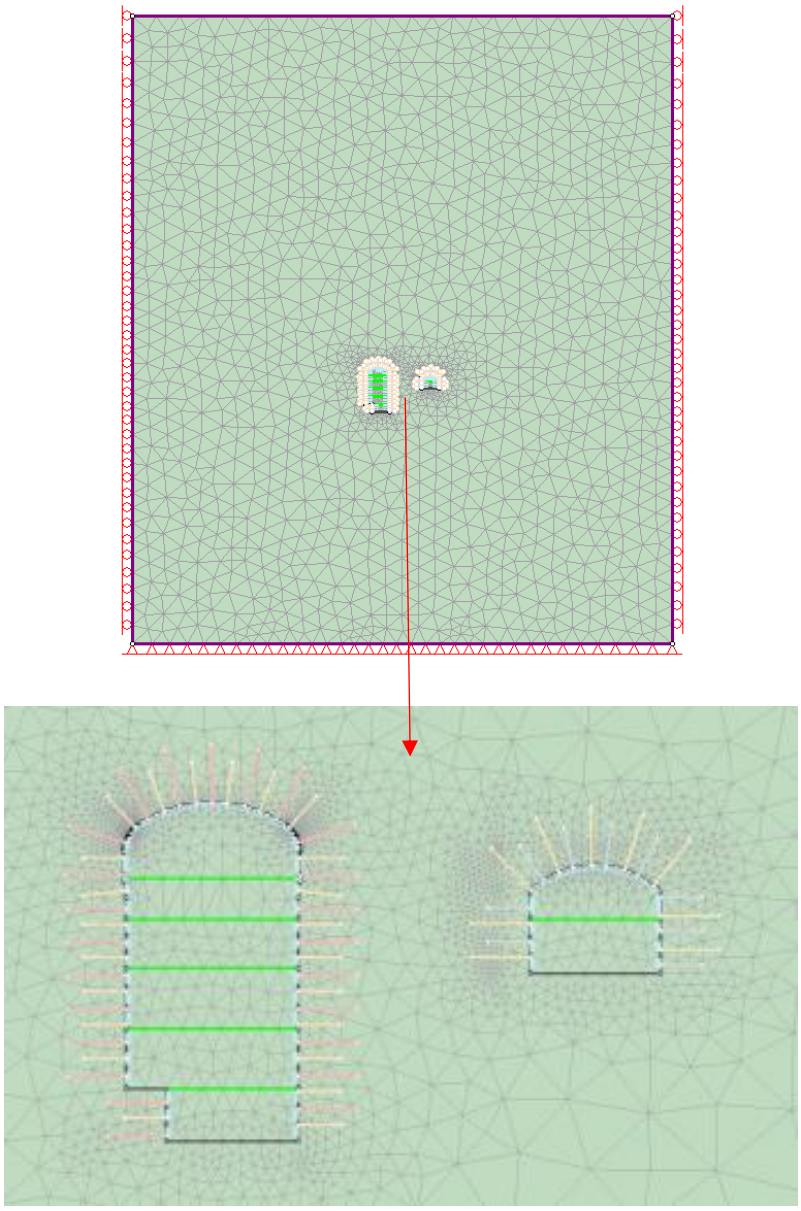


Figure 5-1 Finite element model and boundary conditions

Table 5-1 Gravitational loading for surrounding rock

Rock class	Buried depth	Rock unit weight	Overburden gravitational loading
	m	kN/m³	MPa
II	304.5	27	8.2
III	304.5	26.5	8.1

Prior to application of rock supports, stress release ratio of the surrounding rock takes 50% based on experience, which means that load to be borne by the supporting measures is assumed to be 50% of the ground in-situ stress at the corresponding location.

6 Calculation Results

6.1 Rock class II (Basic design supporting scheme)

According to bid documents, annexes, section VII, annex 5, 07 powerhouse drawings, supports of the powerhouse and transformer caverns is as below and shown in Figure 6-1.

(1)Powerhouse cavern

Roof: rock dowels, φ32mm, spacing 2.0m, L=8.0m.

Side wall: rock dowels, φ32mm, spacing 2.0m, L=12.0m.

(2)Transformer cavern

Roof: rock dowels, φ32mm, spacing 2.0m, L=8.0m.

Side wall: rock dowels, φ32mm, spacing 2.0m, L=12.0m

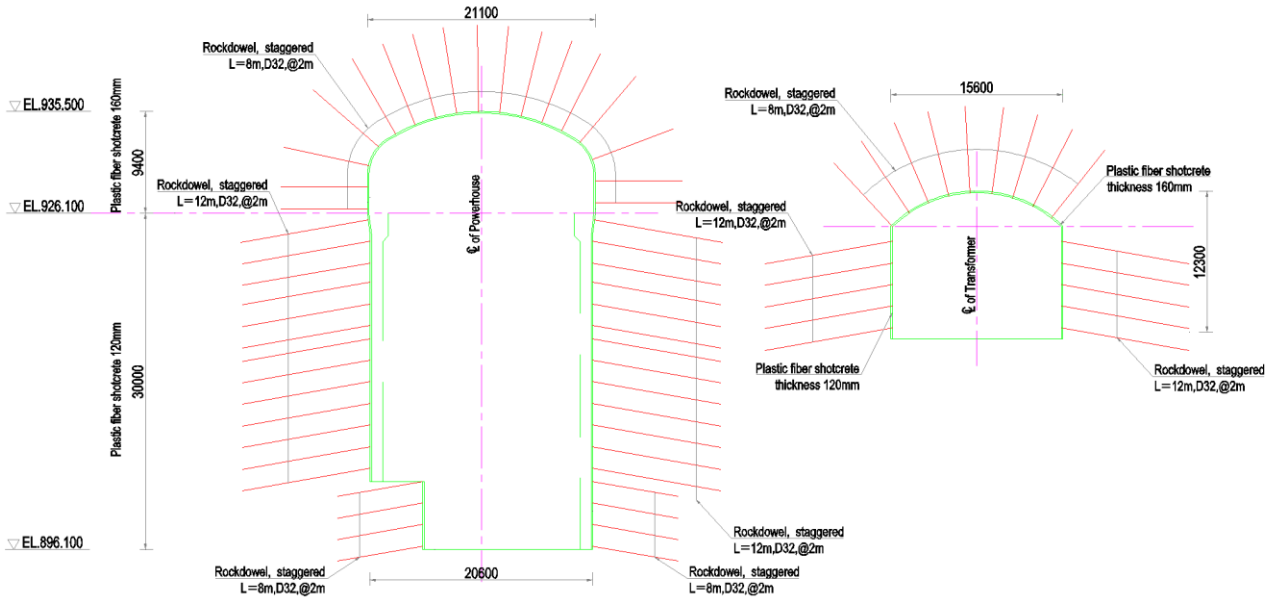


Figure 6-1 Basic design supports of powerhouse and transformer caverns (rock type II)

Calculation result is as shown in Figures 6-2~4.

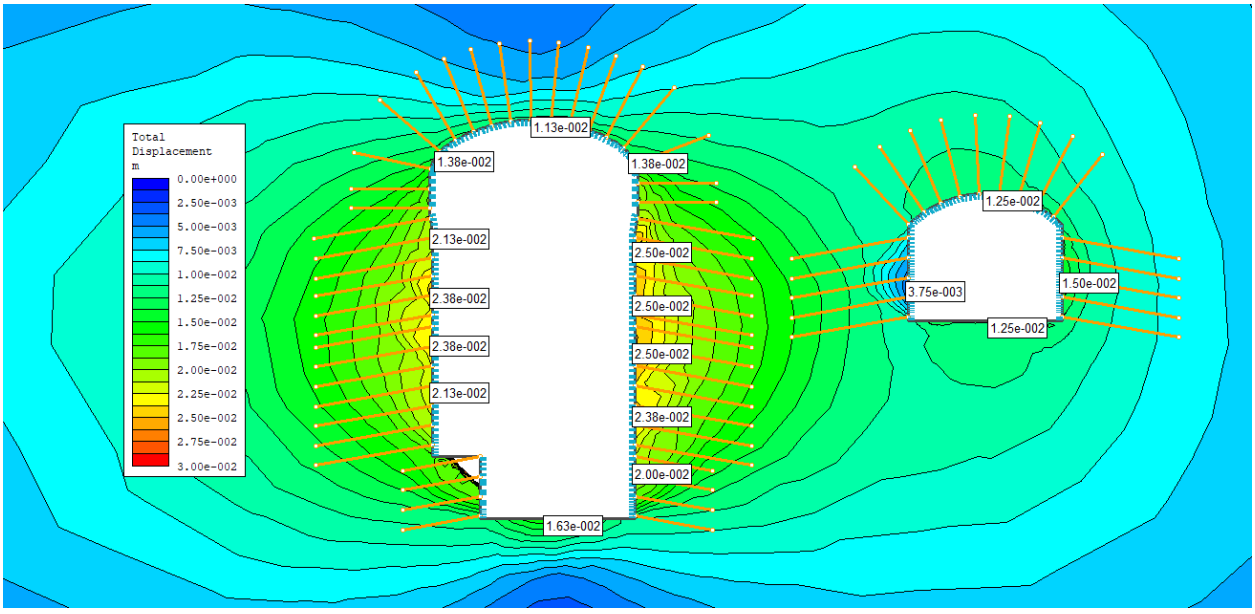


Figure 6-2 Total displacement after support installation (Rock Class II)

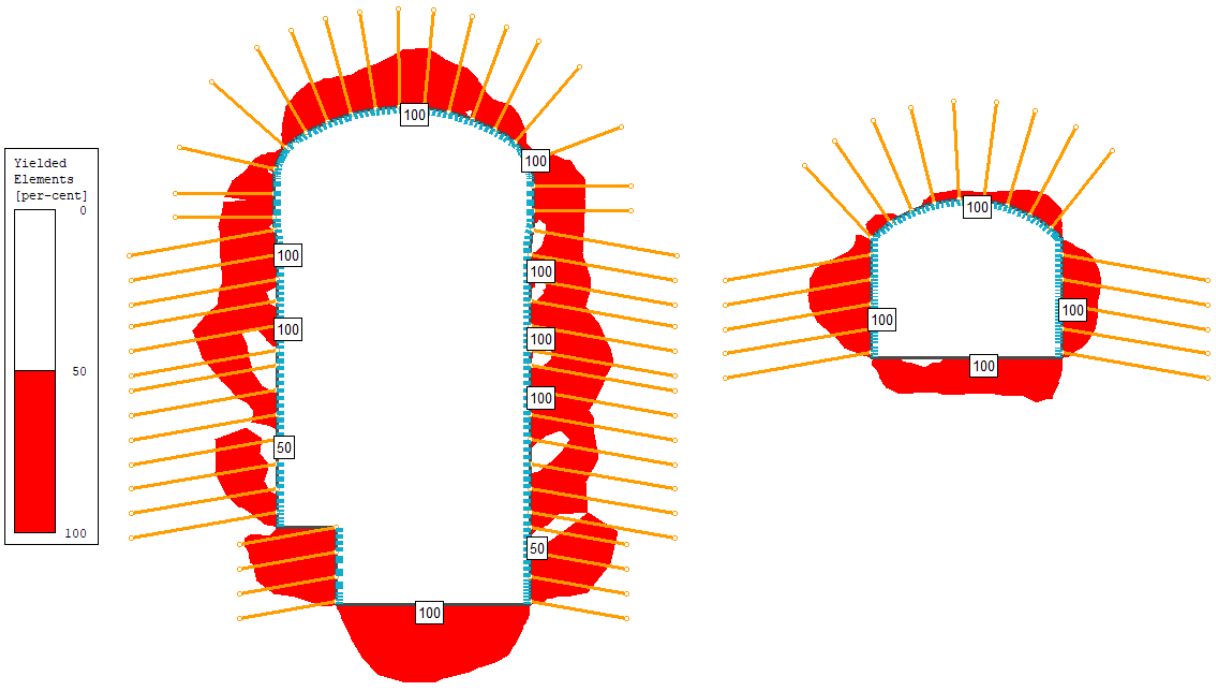


Figure 6-3 Plastic zone after support installation (Rock Class II)

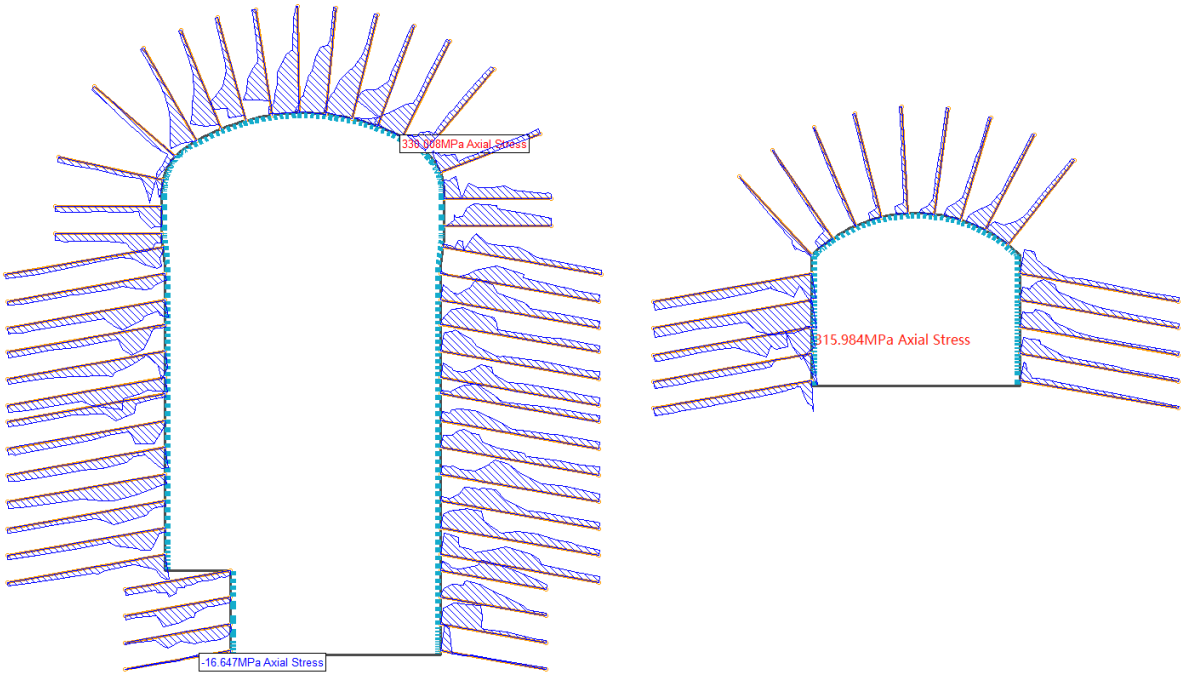


Figure 6-4 Axial stress of rock dowels after support installation (Rock Class II)

6.2 Rock class II (prop supports)

From the calculation results shown above, it can be seen that supports of the powerhouse and transformer

caverns in class II surrounding rock were overdesigned in the basic design stage, mainly the rock dowel length, so a new set of supporting parameters is proposed as below and shown in Figure 6-5.

Furthermore, in order to limit the reflection of the cavern crown effectively, rock bolts are recommended to be applied vertically at the central portion of the cavern crown instead of the rock dowels originally proposed.

(1)Powerhouse cavern

Periphery: rock dowels and bolts, φ32mm, L=7.0m/φ28mm, L=5.0m, spacing 2.0m, staggered. Pre-tensioned bolt instead of central portion of cavern crown (7 bolts).

(2) Transformer cavern

Periphery: rock dowels and bolts, φ28mm, L=7.0m/φ25mm, L=5.0m, spacing 2.0m, staggered. Pre-tensioned bolt instead of central portion of cavern crown (5 bolts)

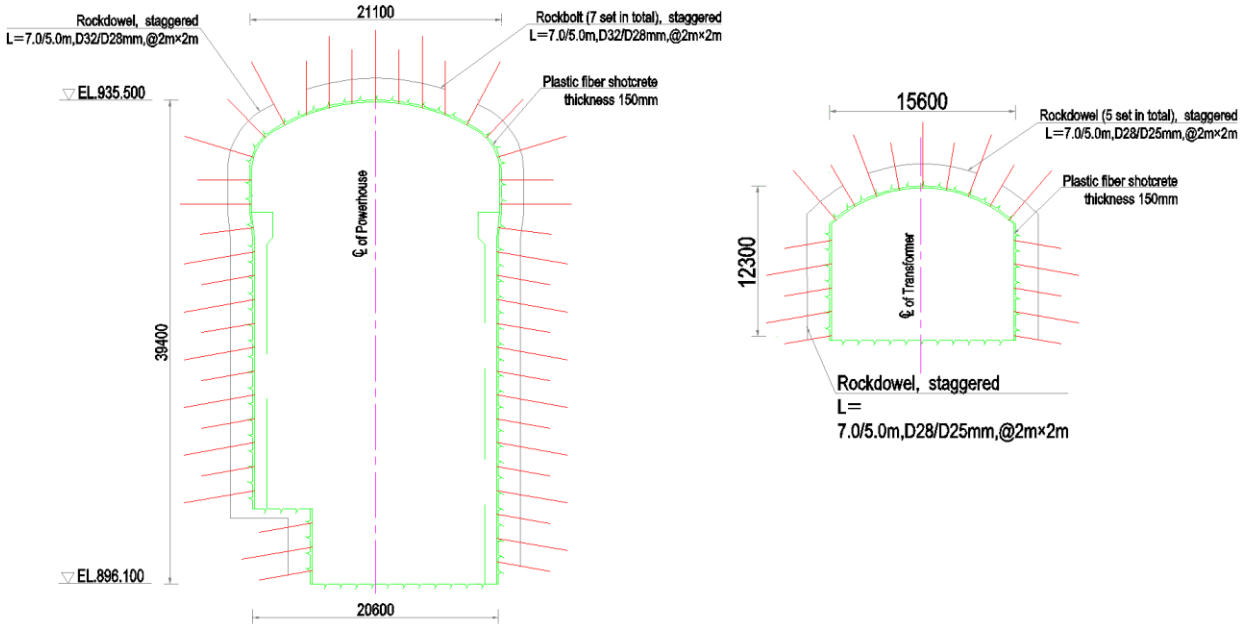


Figure 6-5 Prop supports of powerhouse and transformer caverns (rock type II)

Calculation result is as shown in Figures 6-6~8.

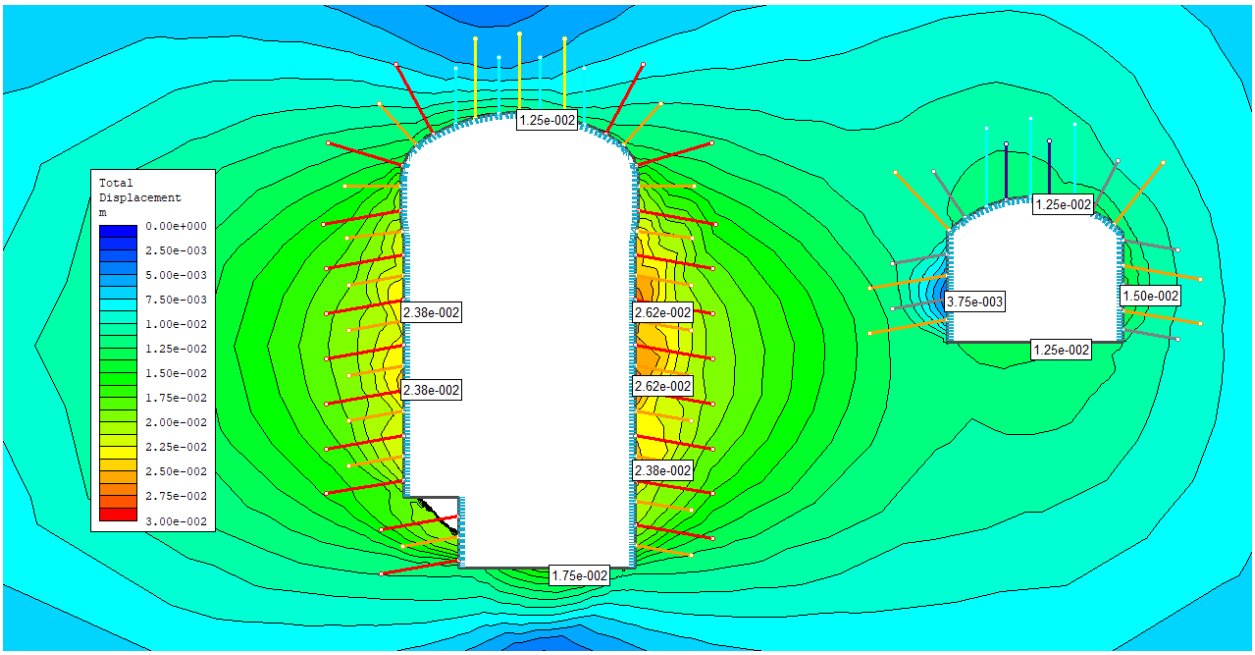


Figure 6-6 Total displacement after support installation (Rock Class II)

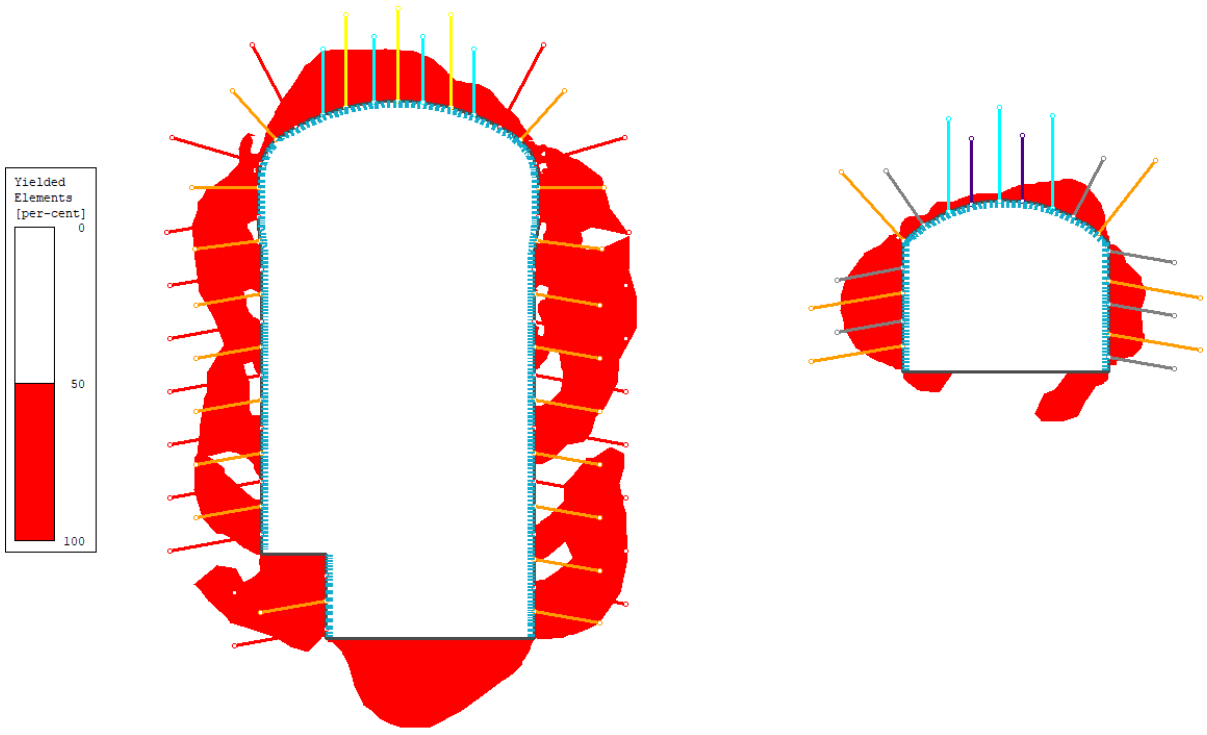


Figure 6-7 Plastic zone after support installation (Rock Class II)

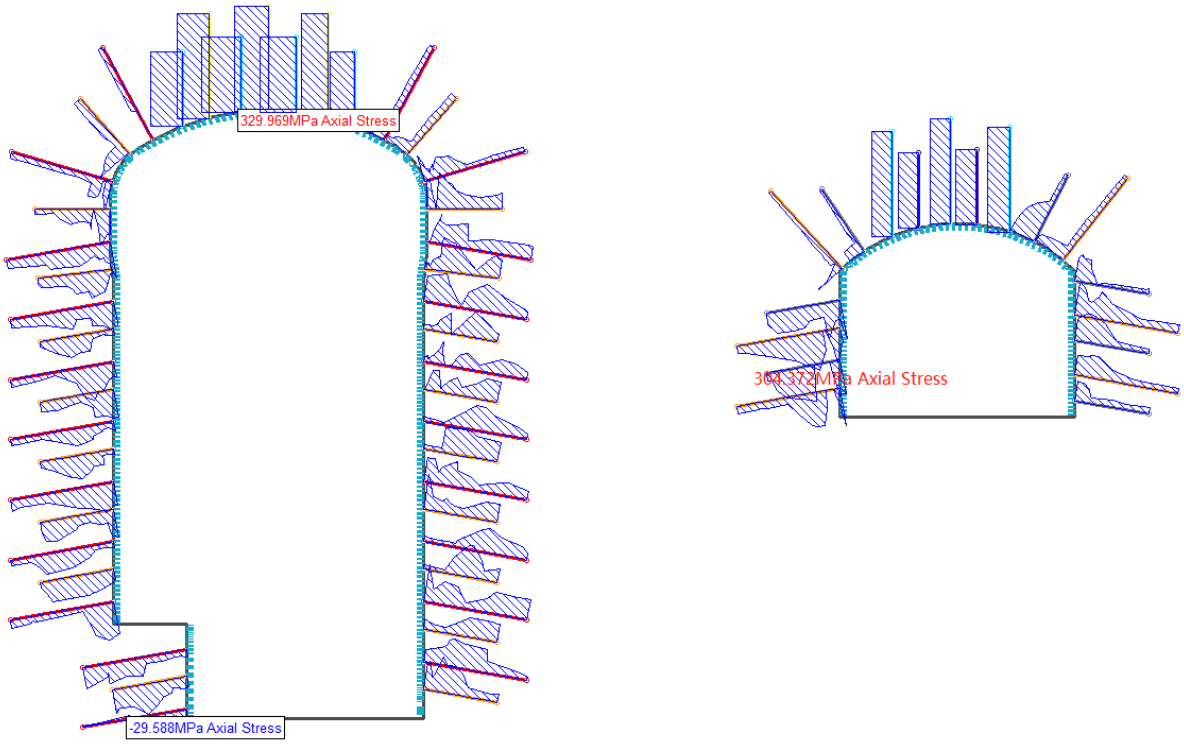


Figure 6-8 Axial stress of rock dowels/rock bolts after support installation (Rock Class II)

6.3 Rock class III (Basic design supporting scheme)

According to bid documents, annexes, section VII, annex 5, 07 powerhouse drawings, supports of the powerhouse and transformer caverns is as below and shown in Figure 6-9.

(1)Powerhouse cavern

Roof: rock dowels, φ32mm, spacing 1.5m, L=8.0m.

Side wall: rock dowels, φ32mm, spacing 1.5m, L=12.0m.

(2)Transformer cavern

Roof: rock dowels, φ32mm, spacing 1.5m, L=8.0m.

Side wall: rock dowels, φ32mm, spacing 1.5m, L=12.0m.

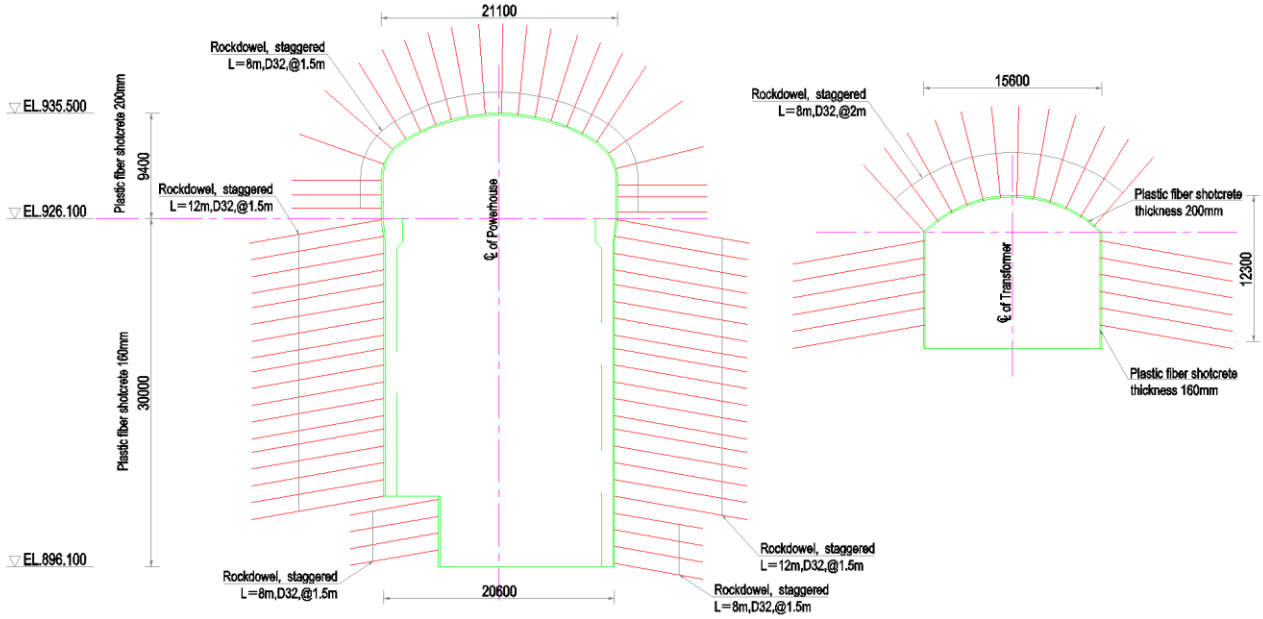


Figure 6-9 Basic design supports of powerhouse and transformer caverns (rock type III)

Calculation result is as shown in Figures 6-10~12.

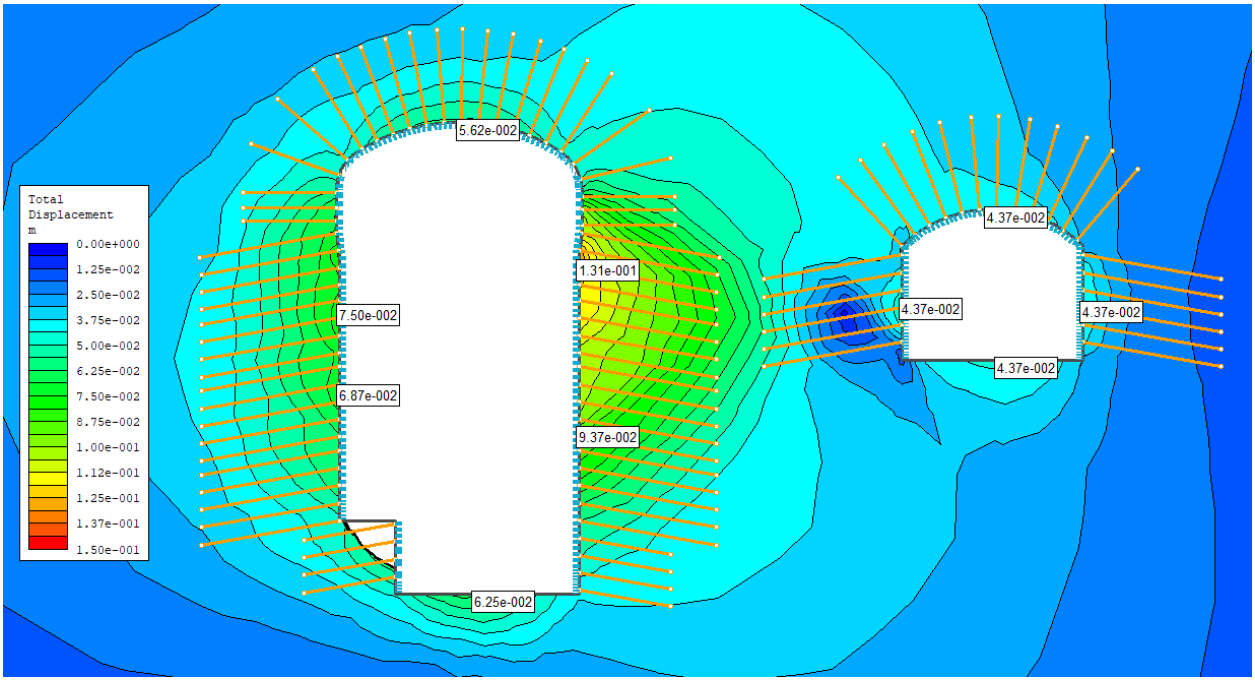


Figure 6-10 Total displacement after support installation (Rock Class III)

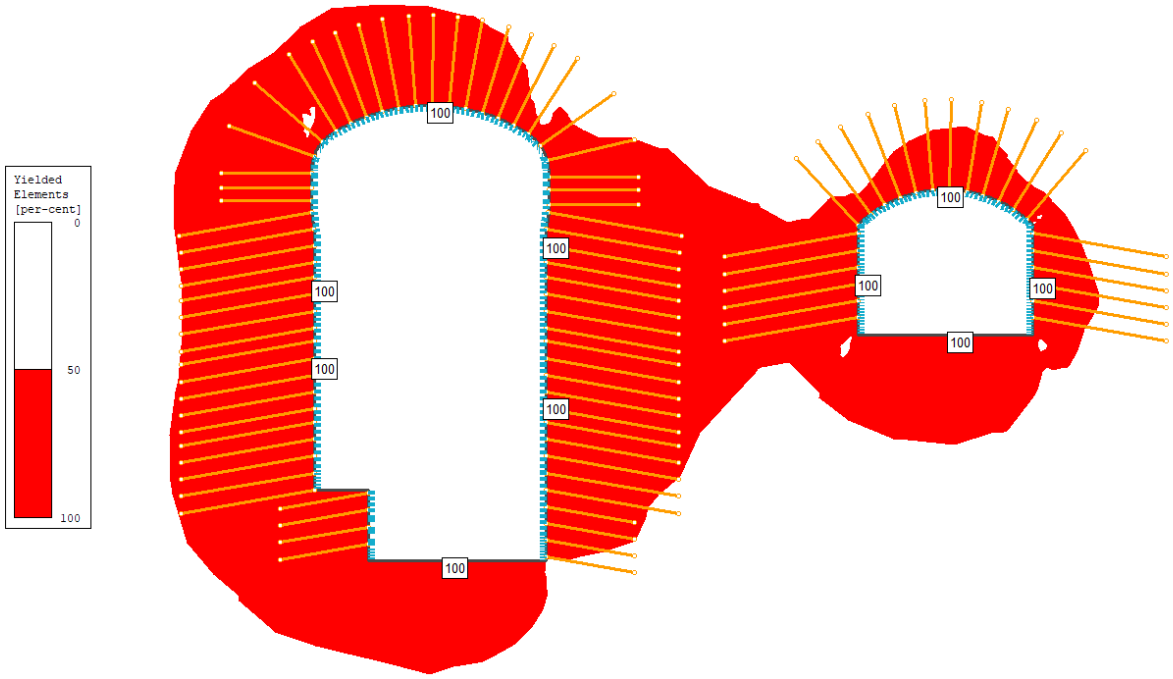


Figure 6-11 Plastic zone after support installation (Rock Class III)

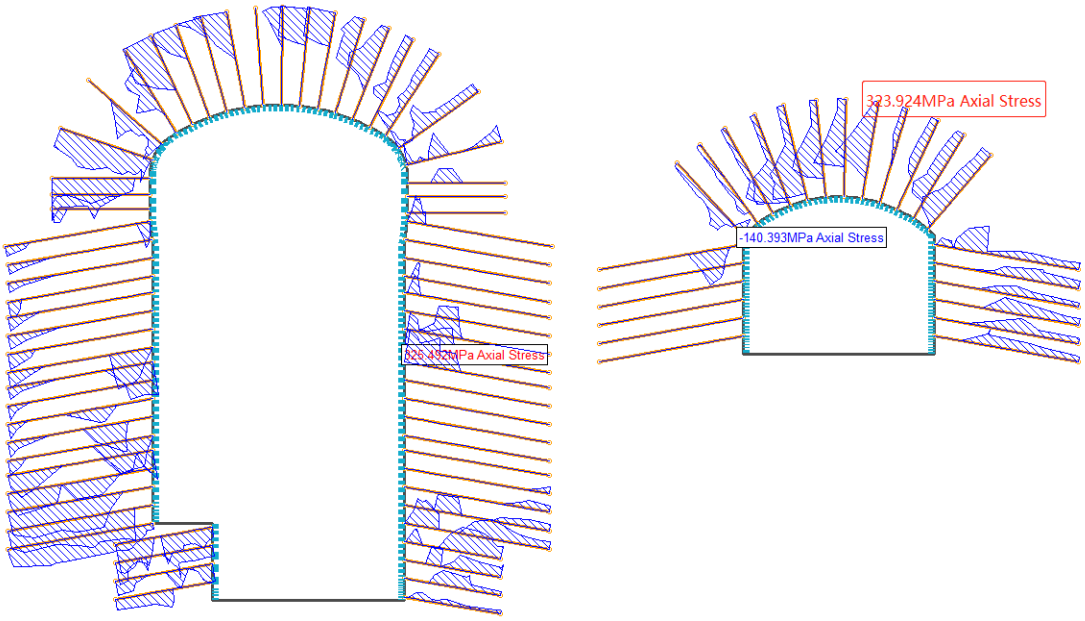


Figure 6-12 Axial stress of rock dowels after support installation (Rock Class III)

6.4 Rock class III (Prop supports)

The proposed supports in this stage are almost the same as that proposed in basic design stage except

supports in the central portion of the cavern crowns, where, rock bolts are proposed to supersede the rock dowels and vertically arranged.

The proposed supports in this stage are as shown in Figure 6-13.

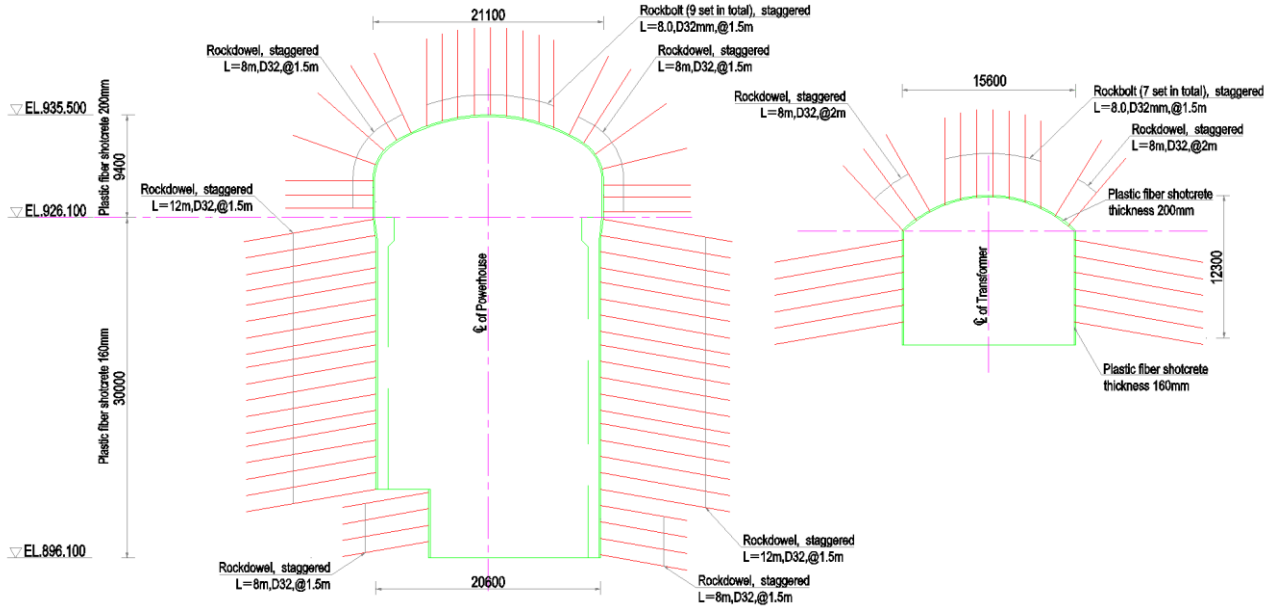


Figure 6-13 Prop supports of powerhouse and transformer caverns (rock type III)

Calculation result is as shown in Figures 6-14~16.

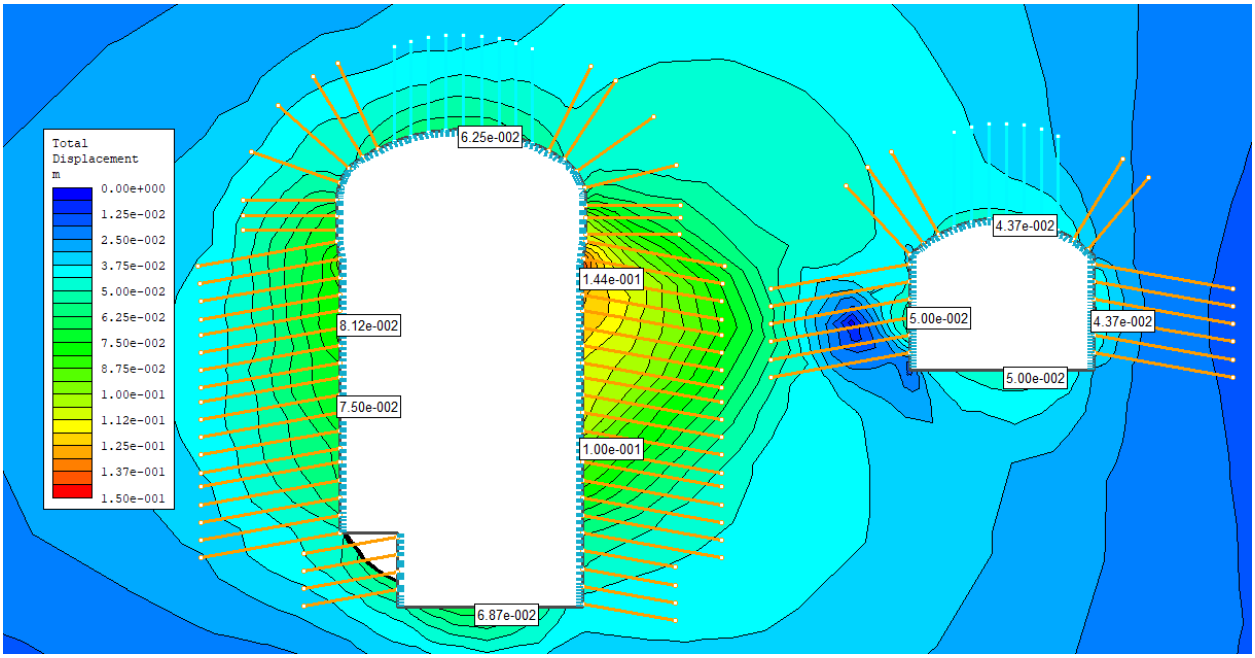


Figure 6-14 Total displacement after support installation (Rock Class III)

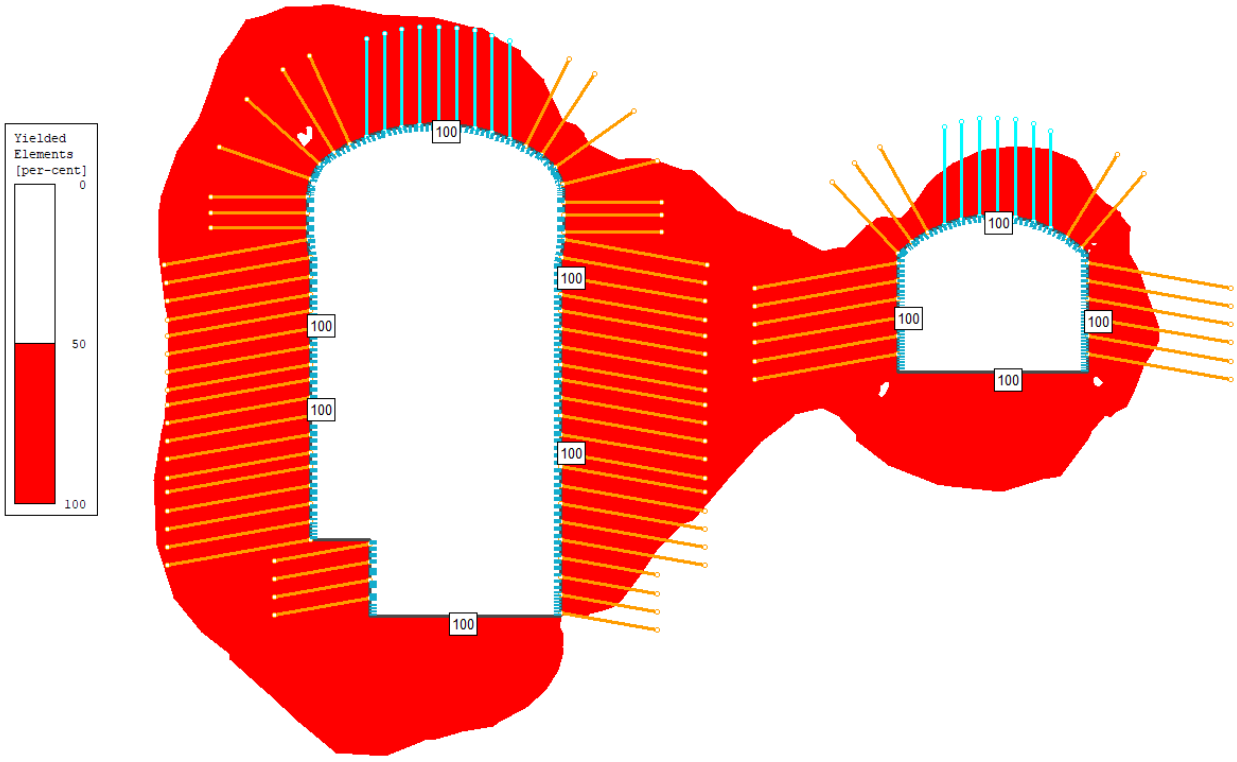


Figure 6-15 Plastic zone after support installation (Rock Class III)

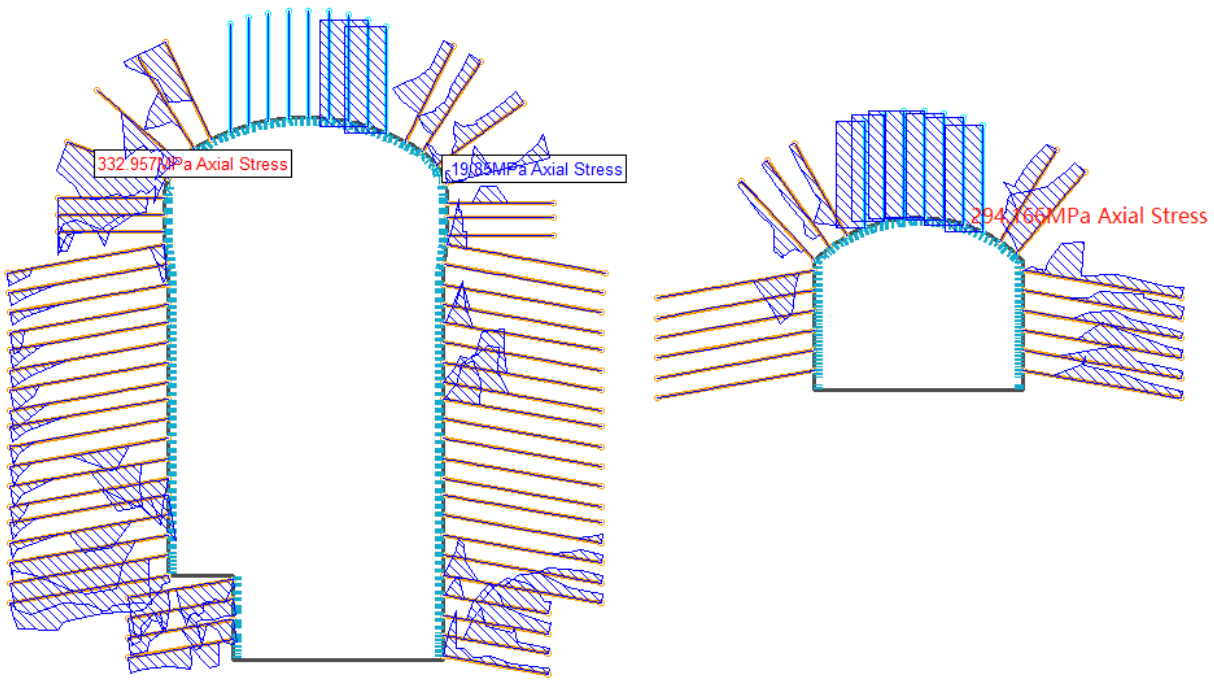


Figure 6-16 Axial stress of rock dowels/rock bolts after support installation (Rock Class III)

7 Wedge Analysis

7.1 Discontinuity Input Data

According to the geological logging of the ventilation tunnel and the main access tunnel of the power house and the geological mapping around the power house, a total of 615 joints are counted. Most joints are closed, a few are slightly open, there is no filling between joints, and a few joints are filled with a small amount of calcium film, rock powder and rock debris.

According to the statistical analysis of Dips software, four groups of joints are mainly developed in the powerhouse area, and the joint characteristics are as follows:

There are 4 groups joints may distribute in the powerhouse, as is shown in Table 7-1~7-2. The stereographic projection of these joints in rock mass in shown in Figure 7-1~7-4. The Mechanical parameter of joints is shown in Table 7-3.

Table 7-1 Occurrence of joints in the powerhouse cavern

Joint NO.	Dip Direction	Dip	powerhouse Direction(Trend)
J1(foliation)	5°	25°	N93°
J2	145°	70°	
J3	200°	72°	
J4	30°	70°	

Table 7-2 Description of joints in the powerhouse cavern

NO.	Type	Occurrence（dip direction/dip）	Structural plane
J1	Foliation	355-10/15-30	spacing is 0.1-0.3m, the local spacing is 0.01-0.05m, the extension > 2m, the surface is straight and rough
J2	joint	135-150/60-75	spacing is 0.5-2m, the extension 2-8m, the surface is straight and rough
J3	joint	198-208/68-75	spacing is 2-5m, the extension 2-8m, the surface is straight and rough
J4	joint	20-45/65-72	spacing is 0.5-2m, the extension 0.5-4m, the surface is straight and rough

Table 7.3 Mechanical parameter of joints in the powerhouse cavern

JONIT TYPE	JRC	JCS	C	Φ
		（MPa）	（MPa）	（°）
Foliation(J1)	6	60	0.20	35.0
lithoclasts cemented (J2~J6)	8	45	0.15	28.8

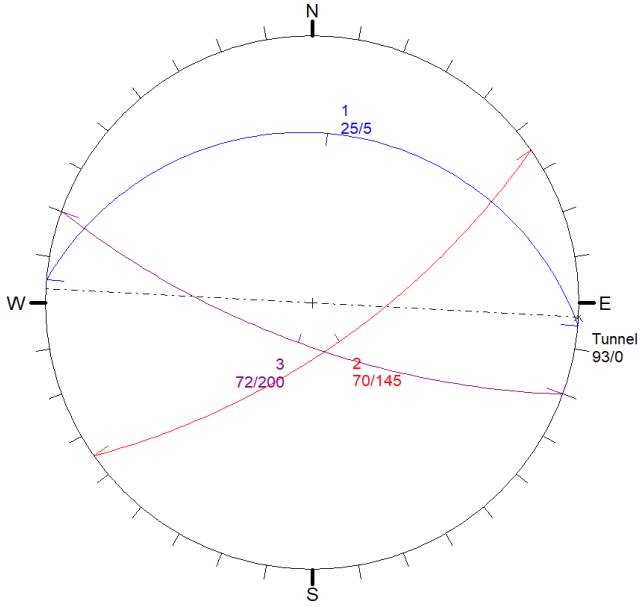


Figure 7-1 Stereographic projection of the joins J1/J2/J3

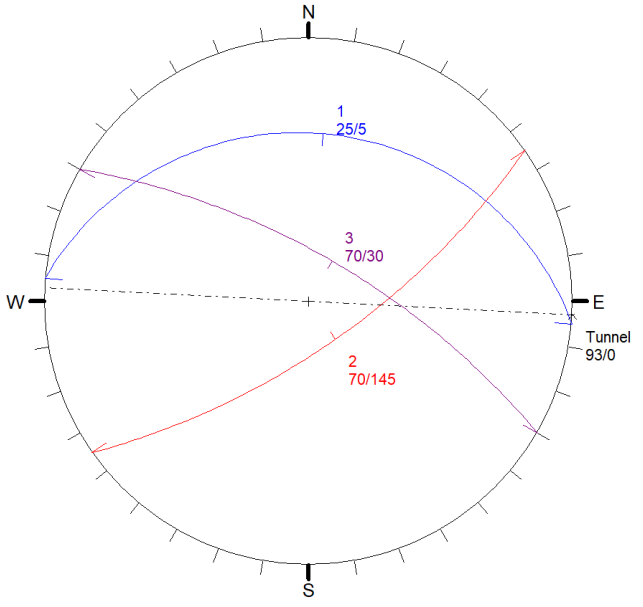


Figure 7-2 Stereographic projection of the joins J1/J2/J4

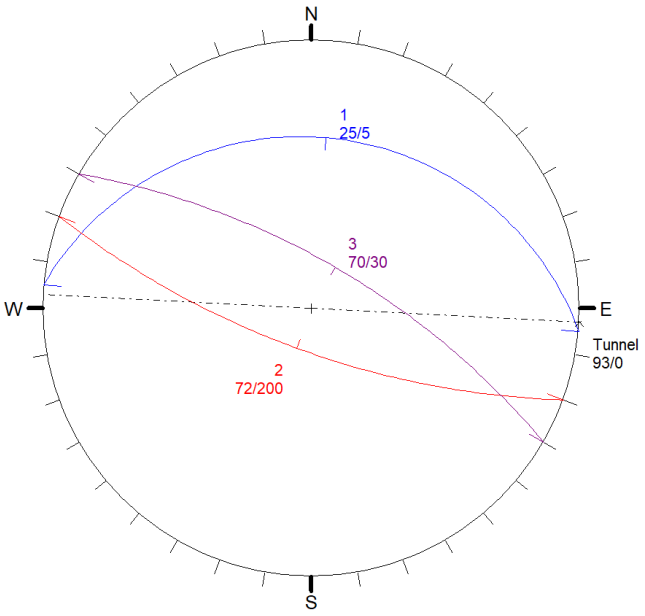


Figure 7-3 Stereographic projection of the joins J1/J3/J4

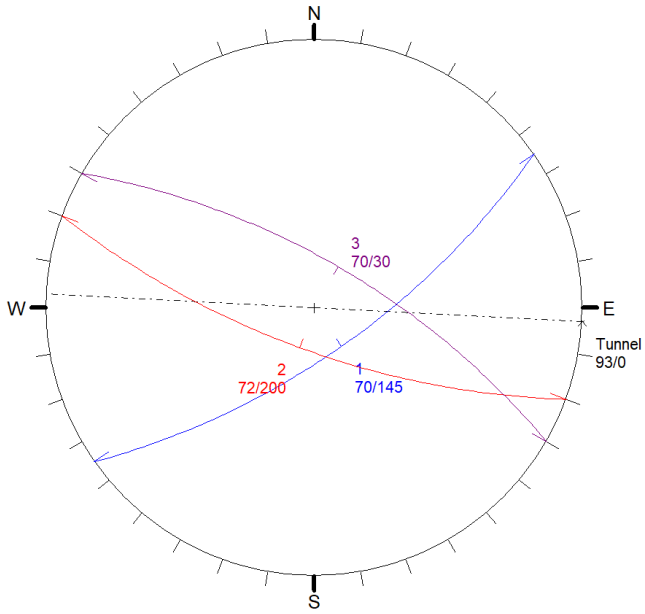
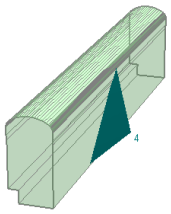
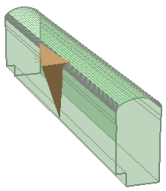
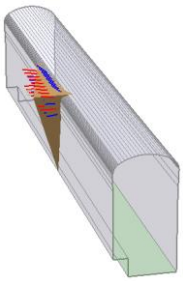
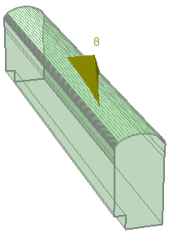
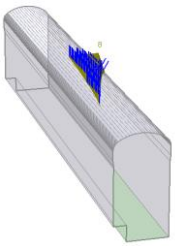


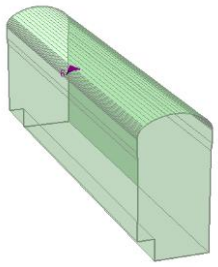
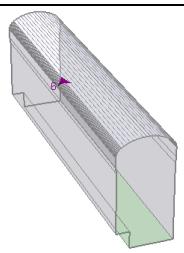
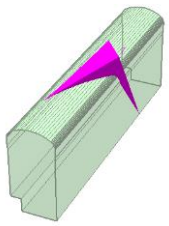
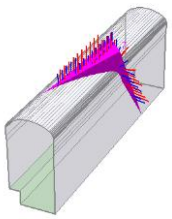
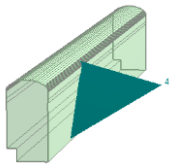
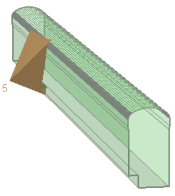
Figure 7-4 Stereographic projection of the joins J2/J3/J4

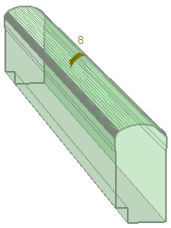
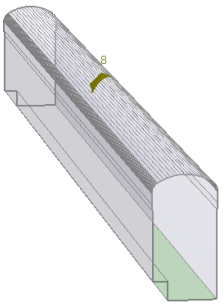
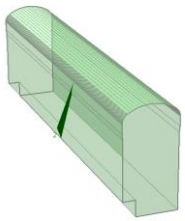
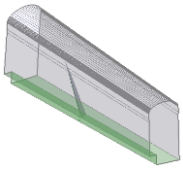
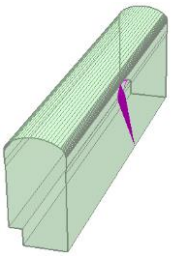
7.2 Wedge Stability Analysis

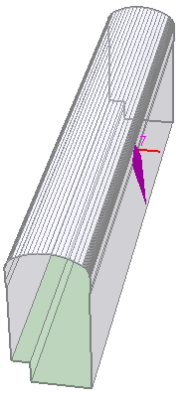
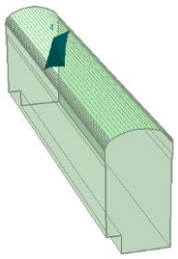
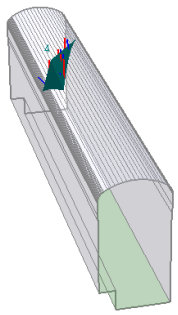
According to the wedge stability analysis, 4 groups of potential wedges may occur in the excavation periods, which are shown in Table 7.3.

Table 7-3 Instability block search statistics of Powerhouse

No.	Fissure set number	Block volume (m^3)	Maximum block height (m)	Safety factor	Developme nt position	Stability	Graphical presentation of block
1	J1/J2/J3	2622.5	9.27	2.434	Lower right side wall	Stable	
2	J1/J2/J3	1642.5	7.73	1.573	Upper right side wall	Unstable	
After pattern supports				2.132		Stable	
3	J1/J2/J3	516.12	5.78	0	Crown	Unstable	
After pattern support and spot supports with rock dowels of L=5m, Dia.28mm, spacing 1.5m				2.358		Stable	

No.	Fissure set number	Block volume (m^3)	Maximum block height (m)	Safety factor	Development position	Stability	Graphical presentation of block
4	J1/J2/J4	1.45	0.66	0	Upper left side wall	Unstable	
After pattern supports				22.74		Stable	
5	J1/J2/J4	1311.8	10.94	1.361	Upper left side wall	Unstable	
After pattern supports				2.325		Stable	
6	J1/J3/J4	13786	32.82	9.9	Lower right Side wall	Stable	
7	J1/J3/J4	11010	30.39	12.34	Lower left Side wall	Stable	

No.	Fissure set number	Block volume (m^3)	Maximum block height (m)	Safety factor	Development position	Stability	Graphical presentation of block
8	J1/J3/J4	36.9	2.19	12.34	Crown	Unstable	
After pattern supports				7.358		Stable	
9	J2/J3/J4	56.9	1.79	0	Lower left side wall		
After pattern supports				2.22		Stable	
10	J2/J3/J4	74.7	1.78	0	Lower right side wall		

No.	Fissure set number	Block volume (m^3)	Maximum block height (m)	Safety factor	Development position	Stability	Graphical presentation of block
After pattern supports				2.2		Stable	
11	J2/J3/J4	443.8		11.62	0.875	Unstable	
After pattern support					2.03	Stable	

8 Conclusions

(1) For rock class II with basic design supports, rock bolts are quite outcropped the plastic zone, rock bolt stress at deeper section is relatively smaller than allowable stress, showing that the supports in the basic design were overdesigned and can be optimized. Contractor proposes to reduce the rock bolt length in his detail design.

(2) For rock class II with proposed supports, maximum crown and sidewall displacement is 12.5mm and 26.2mm respectively, which accounts for 0.06% and 0.1% of powerhouse span; the maximum rock dowel tensile stress is 330MPa, which is less than its allowable value. Therefore, the proposed supports are appropriate.

(3) For rock class III with proposed supports, maximum crown and sidewall displacement is 62.5mm and 144mm respectively, which accounts for 0.3% and 0.69% of powerhouse span; the maximum rock dowel tensile stress is 326MPa, which is less than allowable strength of rock dowel and rock bolt. Therefore, the proposed supports are appropriate. The difference between the proposed scheme and basic design scheme lies in the supports at the crown, in the proposed scheme, rock bolts in vertical direction are designed to replace the rock dowels designed in the basic scheme.

(4) For wedges potentially exists in the cavern crown and sidewall, UNWEDGE analysis is carried out. The calculation results show that nearly all of the wedges will be stable after pattern supports except 1 wedge exists in the cavern crown which shall be supported by using spot supports besides pattern supports.

(5) During tunneling excavation of the powerhouse and transformer caverns, reasonable excavation and supporting sequence, as well as excavation height and advance, shall be followed to avoid failure of the potential unstable blocks.

9 Annex-Joints Survey Report of Powerhouse Zone